

Computation of Equivalent Moment of Inertia Due to Controlled Frequency in Case of Flywheel-less System Subjected to Peak Torques

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Abstract—In order to eliminate bulky flywheels from the process machine having loads with severe torque fluctuations can be driven by an induction motor with control of input frequency using VVVF inverters. Situation of rise in load torque can be met by reduction in frequency at that instant. Situation of sudden reduction in load torque can be met by increase in frequency, at that instant. This paper deals with computations for such cases using the graphical relation between torque and speed, finally leading to a plot of instantaneous motor torque as a function of time. Based on this experimental work is carried out by giving reduced frequency at the instant applying peak load.

Index Terms— Flywheel, process machine, demand torque, VVVF drive, T-s curve

I. INTRODUCTION

Process machines with tougher duty cycles are required to drive variable demand torque over one cycle of operation. These often need a bulky flywheel to smoothen out variations in the speed of a shaft caused by torque fluctuations. Many machines have load patterns that cause the torque to vary cyclically. Adding bulky flywheel is a solution accepted traditionally. Internal combustion engines with one or two cylinders are a typical example. Piston compressors, punch presses, rock crushers etc. are the other systems that have bulky flywheels. Flywheel is an inertial energy-storage device which transacts mechanical energy and serves as a reservoir. It absorbs mechanical energy by increasing its angular velocity and delivers the stored energy by decreasing its velocity.

“Fig. 1” describes the schematics of an arbitrary process unit P along with usual mechanical power transmission system for torque amplification and speed reduction. In this figure, pulley D2 is a power transmission pulley also acts as a flywheel. Pulley D1 is driving pulley receive power from induction motor M. The arbitrary process machine P makes use of link mechanism or cam mechanism or combination of linkage, cam and gears [1]. For such process unit, at every instant, demand torque changes with respect to time. The arbitrary demand torque characteristic of any process machine can be estimated based on cycle time of operation, process resistance and inertia resistance. These can be detailed based on intended operation and proposed details of partial mechanical design [2, 3].

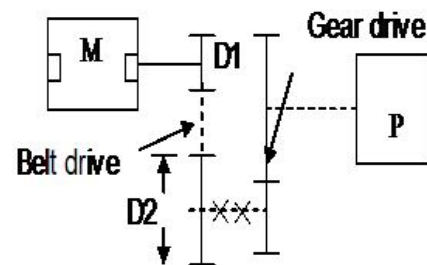


Figure 1. Schematics of an Arbitrary Process Unit, Mechanical Power Transmission & three- phase Induction Motor.

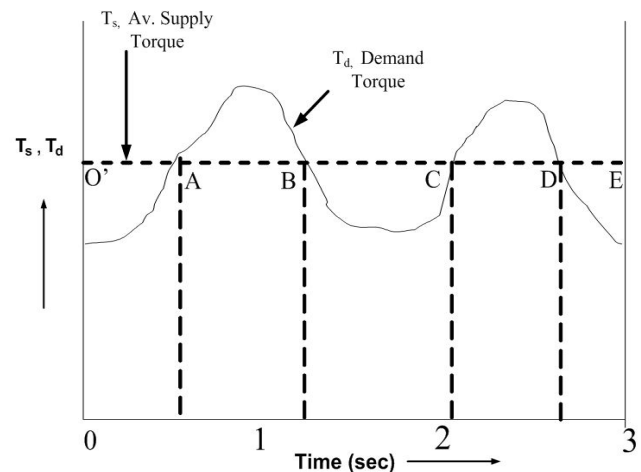


Figure 2. Arbitrary Demand Torque Characteristics

Hence, this variation is cyclic and cycle time is commensurate with rpm of process unit. A typical torque time relation for arbitrary process machine (say mechanical punching press) is shown in the “Fig. 2”. Here, crank speed of input shaft of the process machine is chosen as 20 rpm. Therefore, time for complete cycle of operation should be 3000 m-Sec which gets completed in one rotation of the input link of the process machine. This figure shows that demand torque varies with time, which induction motor cannot generate. Hence, the flywheel is required to make up for the difference of the torque in all time intervals marked in “Fig. 2”. The portion of the system between D2 and process unit is subjected to severe torsional vibrations. Also presence of flywheel with high moment of inertia J in the process machine reduces acceleration, increases weight of engine. It is harder to start and causes fatigue to the components of power trans

mission thereby prolonging equipment functional failure [4]. Therefore, it is desirable to eliminate bulky flywheel from the design of any process machine in general.

With the advent of electric drives and power electronics circuitry using VVVf method, proper energy monitoring is possible to control the power supply to induction motor having low moment of inertia to generate supply torque closely matching with demand torque resulting in elimination of flywheel.

Among different control schemes, a constant volt per hertz principle is chosen to drive three phase induction motor as shown in “Fig. 3”. In this technique, a dynamic model of three phase induction machine is derived from two phase machine. [5], [6], [7]. The equivalence between three phase and two phase machine is based on the equality of the mmf produced in the two phase winding and three phase winding. The stator and rotor variables are transformed to a synchronously rotating reference frame that moves with the rotating magnetic fields. Finally, a dynamic machine model in synchronously rotating and stationary reference frame is developed in per unit by defining the base variables both in $a - b - c$ and the $d - q - o$ variables. Authors have already reported [10], that the above method can be analyzed. It uses VVVF based induction motor drive by controlling input side frequency for better performance, with much smaller system inertia. According to change in demand torque, varying cyclically with respect to time, the requirement of input frequencies to the main drive during different time intervals also changes in order to generate electromagnetic torque matching with demand torque.

the change of load torque to peak value is also less when drive is controlled from input side by frequency control, using VVVf technique, with low moment of inertia [11].

In the present paper, based on above technique, energy is calculated graphically by plotting T-s characteristics at different required frequencies to meet demand load torque characteristics changes suddenly low to high value and vice versa.

II. CLOSED LOOP INDUCTION MOTOR DRIVE WITH CONSTANT VOLTS PER HERTZ CONTROL STRATEGY

In an attempt to simplify the analysis, and to test the proposed system, using standard logics in control system engineering, the demand torque variation of assumed process machine is say as shown in “Fig. 4”. In order to produce same demand torque, an implementation of the constant volts / hertz control strategy for the PWM inverter fed induction motor on per unit basis, is simulated in MATLAB simulink as shown in “Fig. 5” with given mechanical load torque. In PWM inverter, the per unit voltage command through volts / hertz function generator is converted into three phase stationary reference frame variables $a - b - c$ which are further transformed into two phase stationary reference frame $d^s - q^s$ variables and then into synchronously rotating frame in $d^e - q^e$ variables. A PI controller is employed to regulate the slip speed of the motor to keep the motor speed at its set value with respect to frequency given to drive. The major blocks consist of PWM inverter, induction motor with mechanical load [8], [9], [13]. In this scheme mechanical load is varying cyclically in an assumed pattern. As the load torque increases, the speed loop error generates the slip speed command w_{sl} through proportional-integral controller and limiter. The slip is added to the speed feedback signal w_r to generate the slip frequency command w_e . The slip frequency command generates the voltage command V through a volts/hertz function generator. A step increase in slip frequency command w_e produces a positive speed error and the slip speed w_{sl} is set at the maximum value. The drive accelerates due to changes in the frequency and current, producing the torque, matching with demand torque. The drives finally settle at a slip speed for which motor torque balances the load torque. Hence, for varying load torque with respect to time, the drive generates electromagnetic torque which almost matches with demand torque of the process machine.

III. LOCUS OF OPERATING TIME

Here, two cases of varying load torque are considered as shown in “Fig. 4”. In Case 1, load torque suddenly changes from low to high value. In case 2, the load torque changes from high to low value.

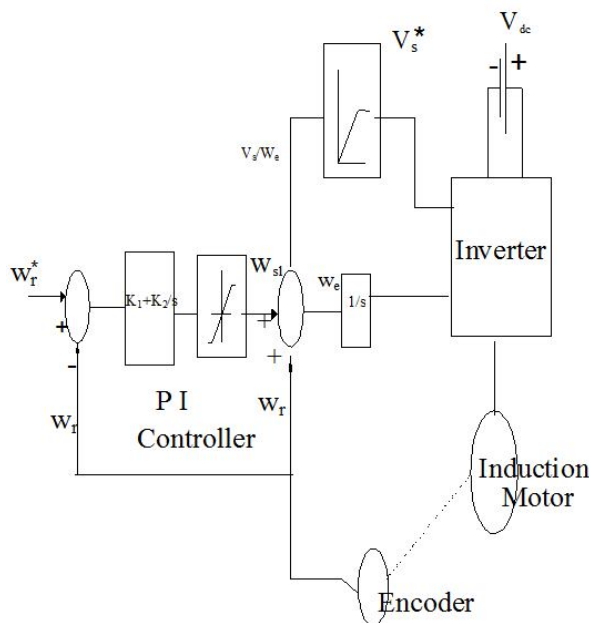


Figure 3. Induction Motor Drive with Closed Loop Volts / Hertz Control.

Hence, problems occurring due to the presence of large flywheel between induction motor and process machine are eliminated. It is observed that required effective energy transaction from rotational masses to shaft of the motor to match

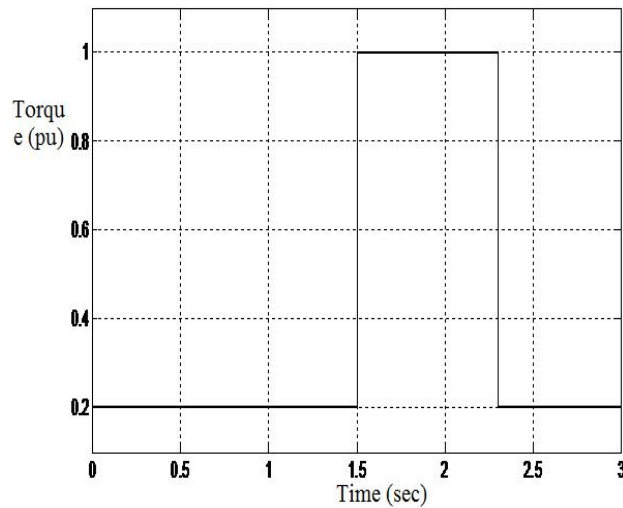


Figure 4. Demand Torque characteristic of a specific Process Machine.

A. Sudden Increase of Load Torque from Low to High Value

From $t = 0$ to 1.5 sec as shown in “Fig. 4”, value of load torque is at low value, hence required frequency to generate electromagnetic torque matching with demand torque is 50 Hz, which is say at point A on torque slip characteristics plotted at 50 Hz shown in “Fig. 6A”, where induction motor is operating on motoring mode. At $t = 1.5$ sec, the torque suddenly rises to a peak value. In order to meet sudden rise in load torque, required frequency for induction motor, using VVVF method is, say, f_1 where $f_1 < 50$ Hz. At this instant, load torque changes its position from A (on T-s curve at 50 Hz) to D point which is on T-s curve plotted at frequency f_1 . The path required to reach A to D point is from A to B, B to C and C to D. When load torque was at low value, induction motor was operating in motoring mode but as soon as load torque suddenly rises to peak value, induction motor shifts its motoring mode to generating or braking mode at frequency f_1 which travels from A to B, B to C to meet the required load torque. C is a point where induction motor runs at synchronous speed corresponding to frequency f_1 and

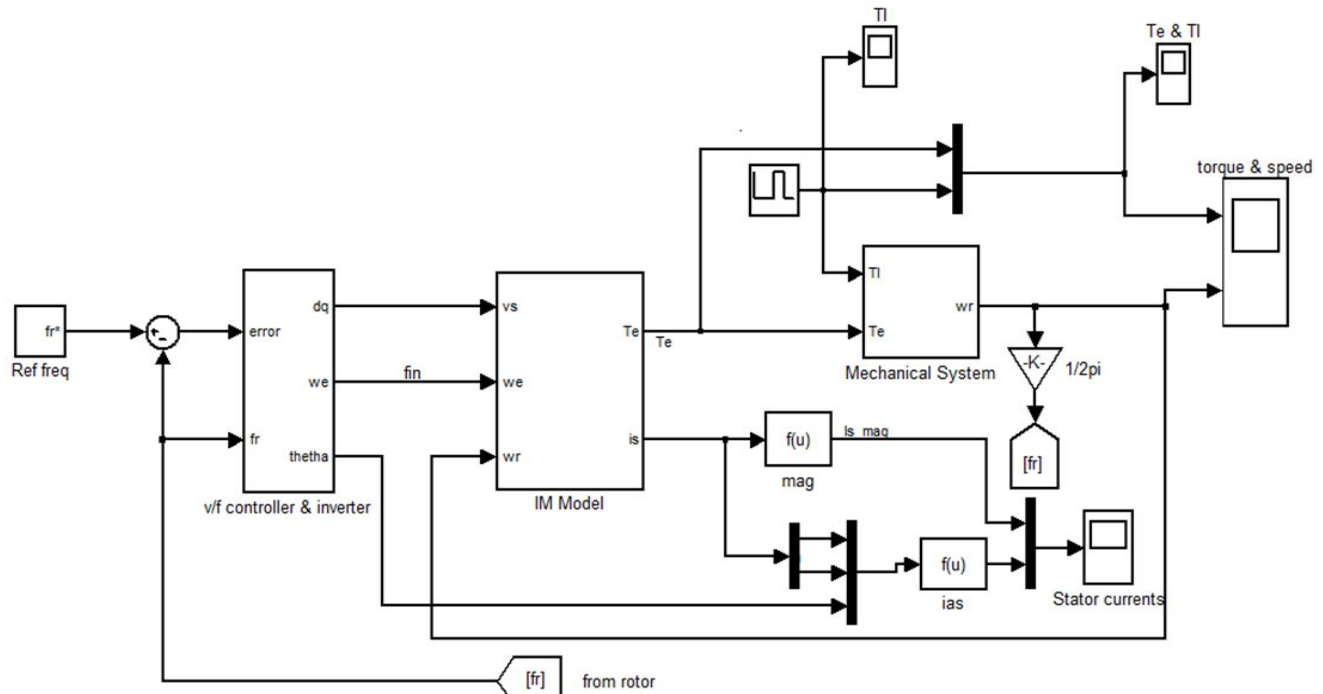


Figure 5. Complete Induction Motor Model with PWM Excitation and Mechanical System along with v/f control scheme in MATLAB simulink

changes its operation from generating mode to motoring mode to reach the point D to generate electromagnetic torque equal to load torque. Hence, by plotting T-s curve at 50 Hz and at frequency f_1 , generating and motoring electromagnetic torques are calculated with speeds varying from A or B to D. Similarly, from “Fig. 6B”, same variations of speeds are calculated at different instant of time when speed of induction motor suddenly reduces to low value because of rise in peak load. Finally, required energy is calculated graphically by plotting generating and motoring electromagnetic torque with respect to different instant of time based on two graphs shown in “Fig. 6A” and “Fig. 6B” to meet demand torque characteristics replacing bulky flywheel.

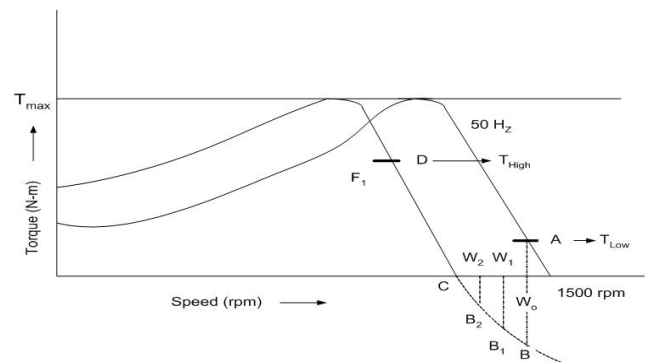


Figure 6A. Flow of energy path of induction motor for sudden increase of load torque.

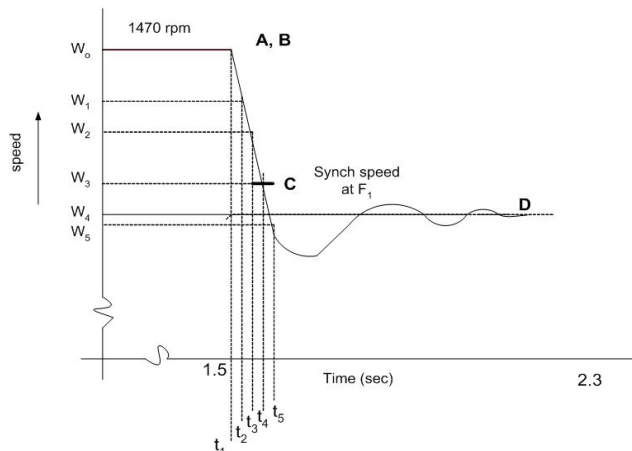


Figure 6B. Reduction of speed of induction motor for sudden increase of load torque.

B. Sudden Decrease of Load Torque From High to Low Value

At $t = 1.5$ to 2.3 sec, shown in “Fig. 4”, value of load torque is at high value, hence required frequency to generate electromagnetic torque matching with demand torque is say at frequency, f_1 , which is a point D on torque slip characteristics plotted at that frequency shown in “Fig. 7A”. Here, induction motor is operating on motoring mode. At $t = 2.3$ sec, the torque suddenly decreases to low value. In order to meet sudden decrease in load torque, required frequency given to induction motor, using VVVF method is say at 50 Hz where $50 \text{ Hz} > f_1$. At this instant, load torque changes its position from D point (on T-s curve at F_1) to A point (T-s curve plotted at 50 Hz). The path required to reach D to point A is from D to E and E to A. Here induction motor operates only in motoring. Hence by plotting T-s curves both at frequency f_1 and at 50 Hz, electromagnetic torques are noted down at different speeds varying from D to A. Similarly, from “Fig. 7B”, same variations of speeds are calculated at different instants of time when speeds of induction motor suddenly increase to high value because of decrease in load torque. Finally, required energy is calculated graphically by plotting electromagnetic torque with respect to different instant of time based on two graphs, shown in “Fig. 7A” and “Fig. 7B” to meet demand torque characteristics.

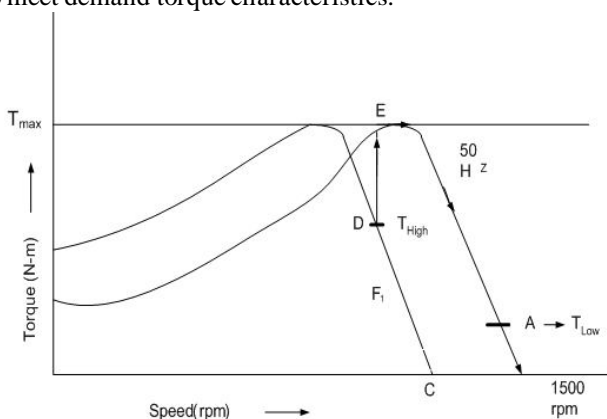


Figure 7A. Flow of energy path of induction motor for sudden decrease of load torque.

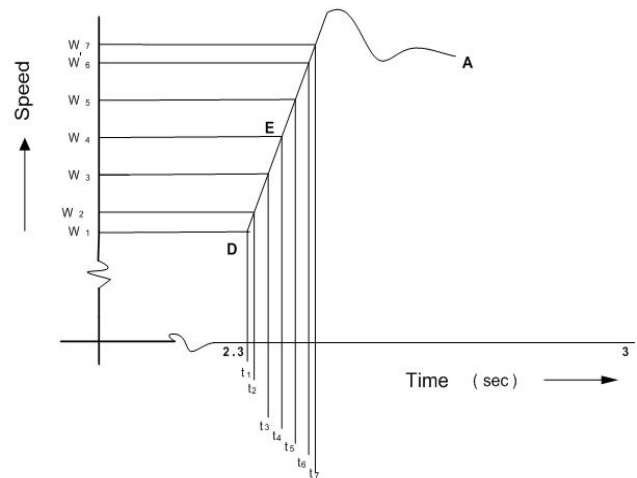


Figure 7B. Increase of speed of induction motor for sudden decrease of load torque.

IV. CASE STUDY

A process machine is so selected which comprises of some linkage mechanism as a main processor. The total cycle time of the process machine is 3000 m-Sec. The induction motor rating is three-phase, 415 V , 1 hp with a synchronous speed of 1500 rpm . In this case, the average angular velocity of the input crank of the process unit is chosen to be 20 rpm . This gives torque amplification from motor shaft to the process unit shaft of the order of $1500/20 = 75$. Induction motor generates average supply torque of 0.596 kgf-m (with given torque formula [4]). Thus, the supply torque at the process unit input shaft is $0.596 \times 75 = 44.7 \text{ kgf-m}$. Hence, the hp demand of the process unit with a given formula is

$$\begin{aligned} hp &= \frac{2 \cdot \pi \cdot N \cdot T}{4500} \\ &= \frac{2 \cdot \pi \cdot 20 \cdot (0.596 \times 75)}{4500} \\ &\approx 1.248 \end{aligned}$$

TABLE 1. 1 HP INDUCTION MOTOR DATA TYPE

HP	1 = 0.75 kW
Rated Voltage	415V, $\pm 10\%$ tolerance
Winding Connection	Star
Rated Frequency	50Hz
Pair of poles	2
Rated speed	1500 rpm
Stator Resistance	12.5487 Ω
Rotor Resistance	12 Ω
Stator Leakage Inductance	144.67 mH
Rotor Leakage Inductance	144.67 mH
Mutual Inductance	545.78 mH
Moment of Inertia	0.0018 kg m ²
Friction Factor	0.01

V. SIMULATION AND RESULTS

In order to get desired result, the demand torque characteristic as shown in “Fig. 4”, is imposed on VVVF based induction motor drive. The induction motor drive is simulated in the synchronously rotating reference frame per unit basis using MATLAB simulink [6], [10],[11] [12]. The parameters of the sample induction motor are shown in Table I. After simulation, it is observed that induction motor generates similar type of electromagnetic torque with respect to demand torque as shown in “Fig. 8A”. The required frequency to generate electromagnetic torque similar to load torque when it suddenly rises to peak value is 32.16 Hz. with drop in speed is 88.75 rad/sec as shown in “Fig. 8B” and “Fig. 8C” respectively. Similarly frequency of the supply to the induction motor changes from 32.61 Hz to 50 Hz when load torque decreases to low value. Hence, for general case, knowing the variations in torque during different time intervals, input frequency for the induction motor should be changed suitably.

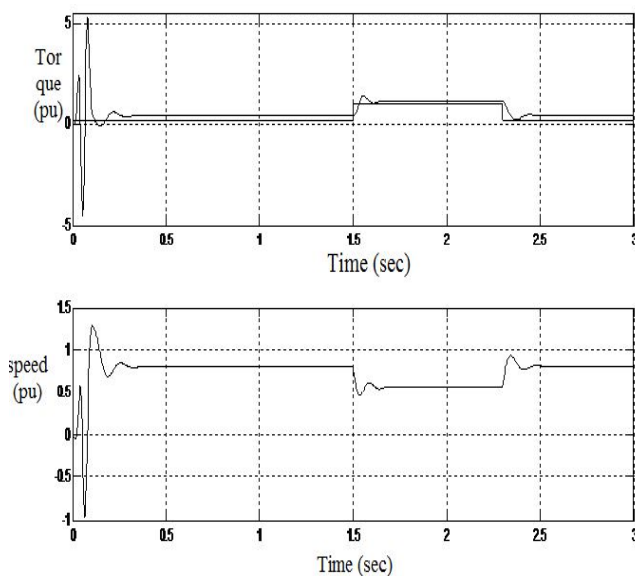


Figure 8A. Electromagnetic torque and speed of induction motor for load torque.

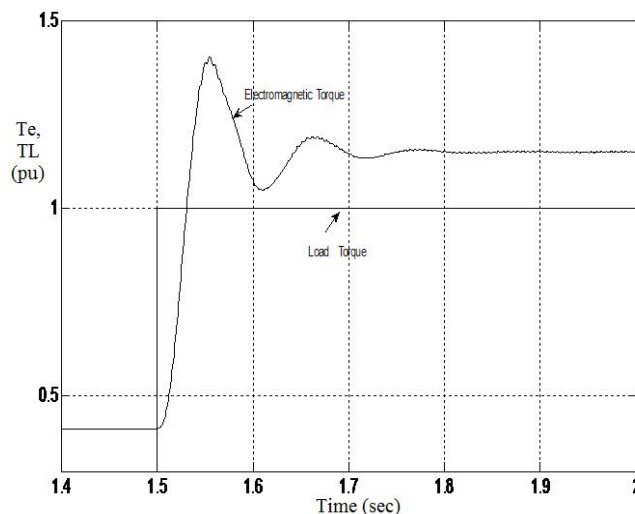


Figure 8B. Electromagnetic torque with respect to rise in load torque.

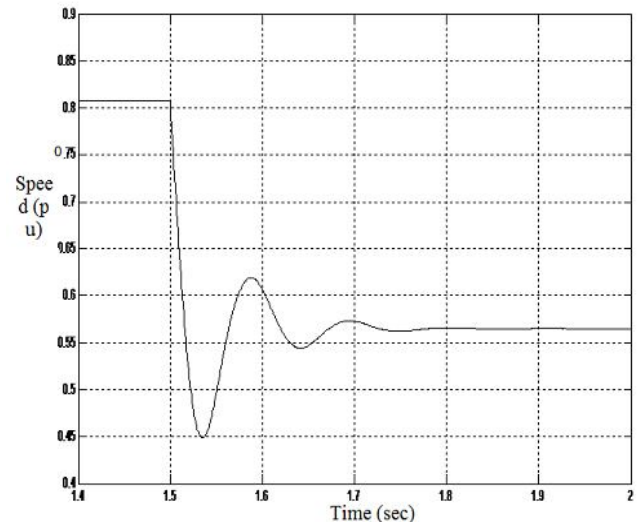


Figure 8C. Drop in speed for increase value of load torque, 88.75 rad/sec.

Based on above cases, torque slip characteristics for 32.16 Hz (shown in “Fig. 9”) and 50 Hz are plotted by writing programme in M file in MATLAB software. It is noted that when load torque suddenly fluctuate to high value, frequency changed from 50 Hz to 32.61 Hz. At that instant, induction motor which was operating in motoring mode (50 Hz) suddenly starts operating in generating mode (32.61 Hz) and follows the path: A to B, B to C. Then it operates in motoring mode from C to D to get desired electromagnetic torque with different values of speeds as shown in “Fig. 6A” (simulation result is shown in “Fig. 9”). Further, these speeds are calculated at different time interval as shown in “Fig. 6B” (simulation result is shown in “Fig. 8C”). Finally based on two curves, energy graph is plotted graphically which is based on available electromagnetic torque at different time as shown in “Fig. 10”. Similar case happens when load torque changes from high to low value. Plot of energy graph at this case is shown in “Fig. 11”. Here, motor follows the operating point from D to E and E to A as shown in “Fig. 7A”. In this case, induction motor operates only in motoring mode while following this path. Hence, based on graphically plotted path, behavior of dynamic nature of load torque is studied.

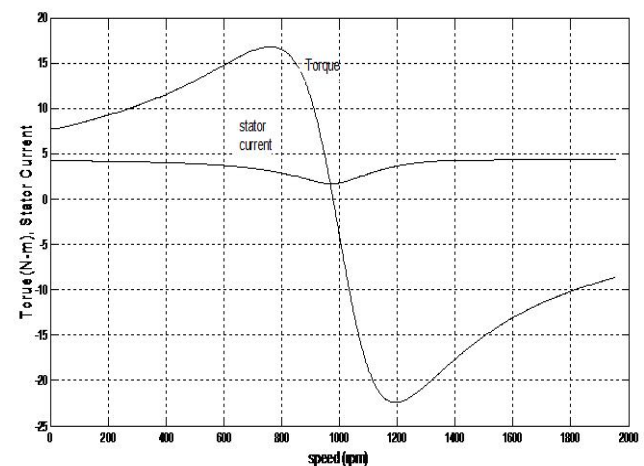


Figure 9. Torque -slip characteristics at 32.61 Hz.

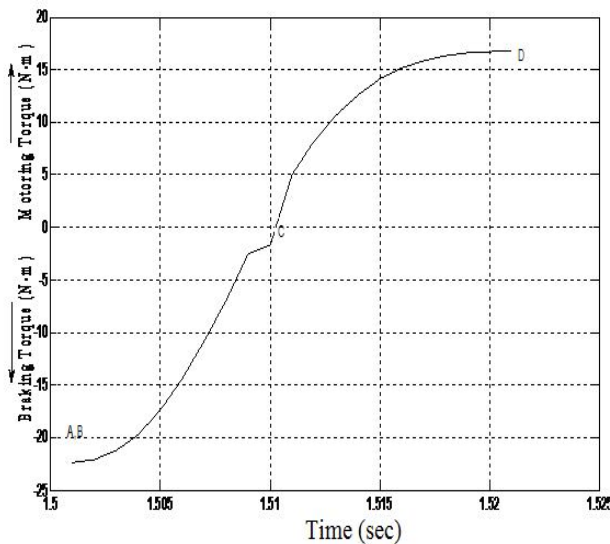


Figure 10. Plot of energy graph, electromagnetic torque vs time for rise in torque.

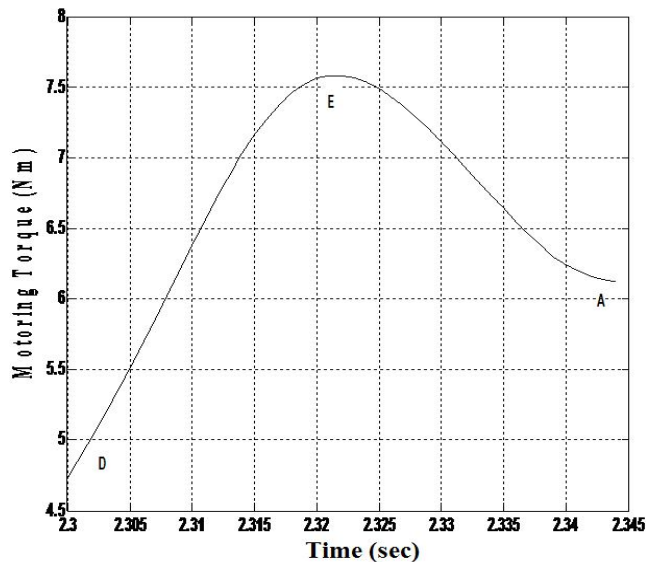


Figure 11. Plot of energy graph, electromagnetic torque vs time for fall in torque.

VI. EXPERIMENTAL WORK

In order to verify the simulation work discussed previously, a simple experiment in laboratory is carried out. In this experimental work, induction motor-generator set is run through variable frequency device (VFD) and drive's input frequency is controlled at the instant of applying sudden peak load in running condition. The nature of speed in the form voltage with respect to time is observed in digital storage oscilloscope (DSO) to show how induction motor changes its operation from generating mode to motoring mode to cope up sudden increase of peak load at that instant.

The block diagram in "Fig. 12" shows the experimental setup in which electrical load is connected to induction motor-generator drive set due to absence of mechanical load. The induction motor is run through variable frequency device (VFD) to control its input side frequency after sudden application of peak load from no load condition. The changes

in speed waveform of the drive set from no load to peak load at reduced frequency is observed in digital storage oscilloscope (DSO) through PM tacho-generator which converts speed into suitable voltage.

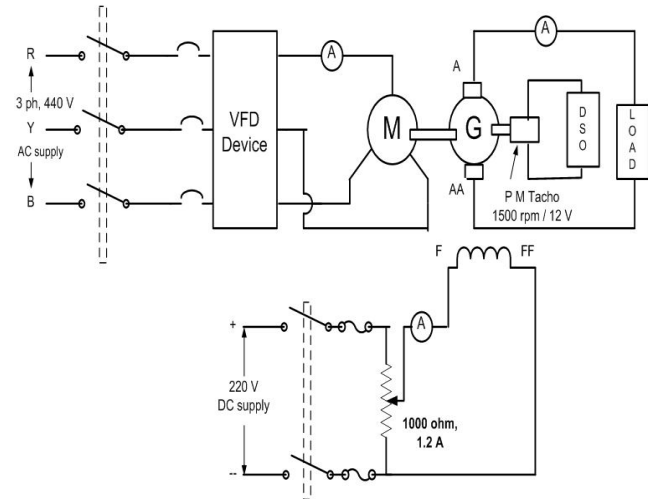


Figure 12. Laboratory experimental set up.

The rating of induction motor is chosen as 3-phase, 3hp, 415V, 7.8 A, 50 Hz, 1480 rpm E class. The rating of DC generator is 3 kW, 220 V, 16 A, shunt type 1500 rpm B class. The rating of VFD device is 2.2 kW, 460 V, Input = 3 phase, 380 - 480 V, 50 / 60 Hz, 6.0 A, Output = 3 phase, 0 - 480 V, 5.0 A, 3.8 KVA and frequency range = 1- 400Hz

VII. EXPERIMENTAL WORK

The simple electrical load characteristics like step input from no load to full load is considered to understand the operation of motor in a better way. In first condition, the motor- generator set is run at constant supply frequency at no load as well as at full load condition. In second condition, reduced frequency is given to set drive when sudden peak load is applied after no load condition running at grid frequency. Reduced frequency at the instant of applying full load helps to understand the behavior of motor in generating mode clearly. To observe speed characteristics waveform in DSO, the PM dynamometer of rating 12 V acts as tacho-generator and is connected to shaft which converts speed into corresponding voltage. Hence, 1500 rpm corresponds to 12 V. In DSO, the attenuation factor chosen is 10.

A. Drive Running at Supply Frequency from no Load to Peak Load

In this condition, induction motor-generator set is run at grid frequency at no load as well as full load condition. The no load speed is 1482 rpm which corresponds to 11.856V. The observed voltage in DSO is 12V as shown in "Fig. 13". After sudden increase of full load, the load current is 7.8 ampere and measured speed is 1436 rpm which corresponds to 11.488V. The observed average voltage in DSO is 11.3 V. The observed stator current at peak load is 8 ampere (peak to peak). The ratio between DC load current to observed stator current calculated as 2.757.

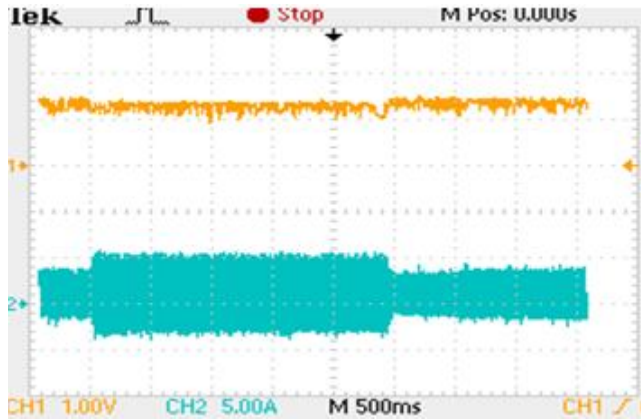


Figure 13. Speed and stator current waveform of induction motor running at constant supply frequency from no load to peak load.

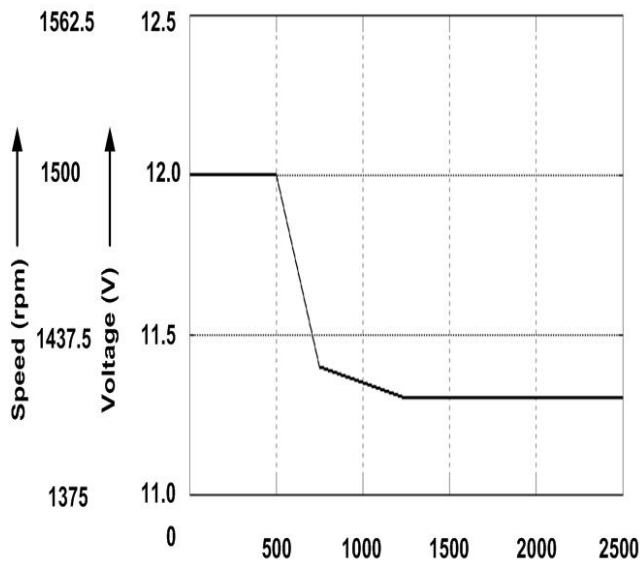


Figure 14. Enlarge plot of Figure 13 considering average voltage (or in terms of speed) w.r.t. time.

“Fig. 14” show the enlarge plot of “Fig. 13” which plotted by considering average value of voltage with respect to time at grid frequency shown in experimental result in DSO.

B. Drive Running at Supply Frequency at no Load and reduced frequency at Full Load

In this condition, induction motor-generator set run at constant supply frequency in no load condition and reduced frequency of 45 Hz given at the instant of applying peak load through VFD. To cope-up this peak load, the induction motor speed reduced to 1284 rpm which corresponds to 10.272 V. The observed average voltage in DSO is 10.5 as shown in “Fig. 15”. Looking into the speed waveform characteristics, the induction motor which was running in motoring mode at 1482 rpm at no load, 50 Hz supply frequency suddenly started to operate in generating mode. The synchronous speed corresponds to 45Hz is 1350 rpm. So, induction motor behaves in generating mode from 1482 rpm to 1350 rpm. After that, to cope up peak load, it runs as a motoring mode from 1350 rpm to 1284 rpm. “Fig. 16” show the enlarge plot of “Fig. 15” which plotted by considering average value of voltage in

DSO with respect to time. This plot shows the operation of induction motor from generating mode to motoring mode clearly.

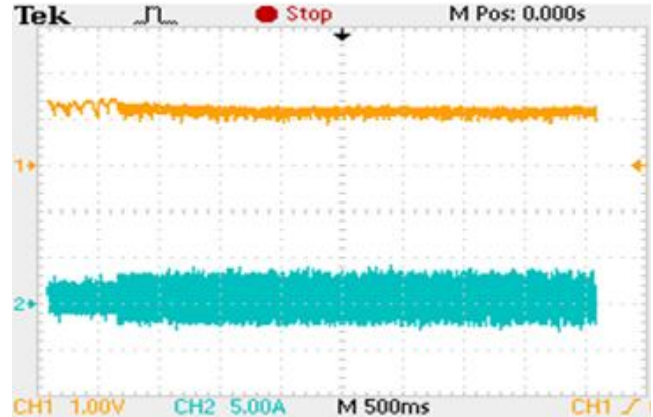


Figure 15. speed and stator current waveform of induction motor from 50 Hz to 45 Hz during peak load.

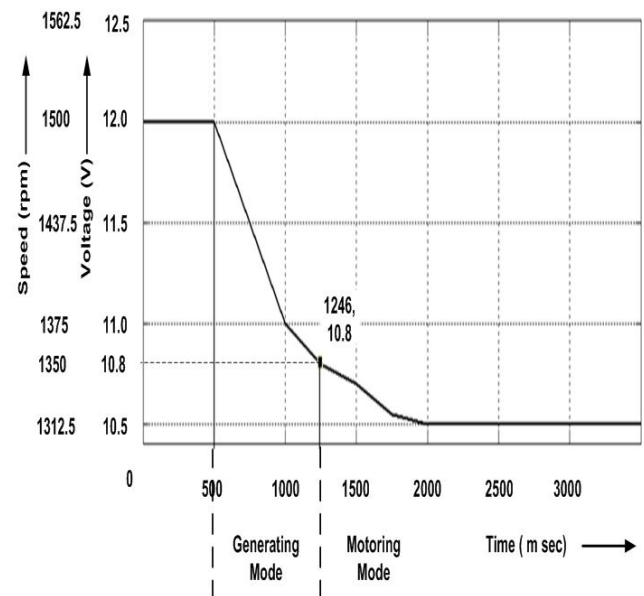


Figure 16. Enlarge plot of Figure 15 by considering average value of voltage (or in terms of speed) w.r.t. time.

The ratio between DC load current to observed stator current calculated as 3.733. The slope of speed characteristics waveform in “Fig. 16” also shows that frequency change is slower from generating to motoring mode when drive run at reduced frequency at instant of applying peak load as compare to motor drive running at grid frequency for the same peak load demand shown in “Fig. 14”.

Table II shows that ratio of load current to observed stator current in DSO at two frequencies given to induction motor drive. This ratio increases when applied frequency is less, which requires less stator current to generate electromagnetic torque matching with peak load demand torque. As power multiplied by load torque corresponds to speed. Therefore, ratio of two powers at two frequencies is

$$\frac{P_{50}}{P_{45}} = \frac{1436}{1284} = 1.118$$

TABLE II. RATIO OF LOAD CURRENT AND STATOR CURRENT

Sr. No.	Frequency (Hz)	Load Current (DC) I_L (Amp)	Stator Current (RMS) (from DSO), I_s (Amp)	Ratio I_L / I_s
1	50	7.8	$04 / \sqrt{2} = 2.828$	2.757
2	45	6.6	$2.5 / \sqrt{2} = 1.7677$	3.733

Assuming same power factor and neglecting all losses, then required stator current of the drive if speed is reduced to 1284 rpm at 50 Hz frequency is

$$1.118 \times 1.7677 = 1.976 \text{ Amp}$$

But, for same reduced speed of 1284 rpm, if given frequency to drive reduces to 45 Hz at the instant of applying peak load, then stator current is only 5 ampere. Therefore, given reduced frequency at peak load demand always draws the less stator current to fulfill the demand which is less than the required stator current of 1.976 ampere if drive runs at constant supply frequency

VIII. CONCLUSIONS

In order to eliminate bulky flywheel from the process machine having wide fluctuation in load torque, it is proposed to control input side power and frequency of the main drive using VVVF technique, to generate electromagnetic torque characteristics almost matching with demand torque characteristics of the process machine. Based on above technique, the required energy of induction motor is calculated graphically by plotting two curves, one is T-s characteristics at different frequencies (based on load torque) and corresponding speed with respect to time at those frequencies. Induction motor changes its operation i.e. from motoring mode to generating mode and then generating to motoring mode to meet demand torque characteristics when load torque sudden changes from low to high value whereas, from high to low value of load torque, operation of induction motor remains in motoring mode only. Hence, by graphically plotting instantaneous torque as a function of time, dynamic behavior can be analyzed.

Experimental results give the proof of behavior of induction motor from generating to motoring mode operation when given frequency is reduced at instant of applying peak load. Also, the required stator current at this reduced frequency is less as compared to stator current required when drive runs at constant grid frequency to fulfill same peak load.

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